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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

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[X] Additional inventors are being named on the separately numbered sheet(s) attached hereto

TITLE OF THE INVENTION (500 characters max)

APPARATUS AND METHOD FOR HIGH RESOLUTION FINGERPRINT CAPTURE AND IDENTIFICATION

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ENCLOSED APPLICATION PARTS *(check all that apply)*

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Signature	Timothy J. Meagher	Date	11/18/03
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PROVISIONAL APPLICATION COVER SHEET

Additional Page

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Figures

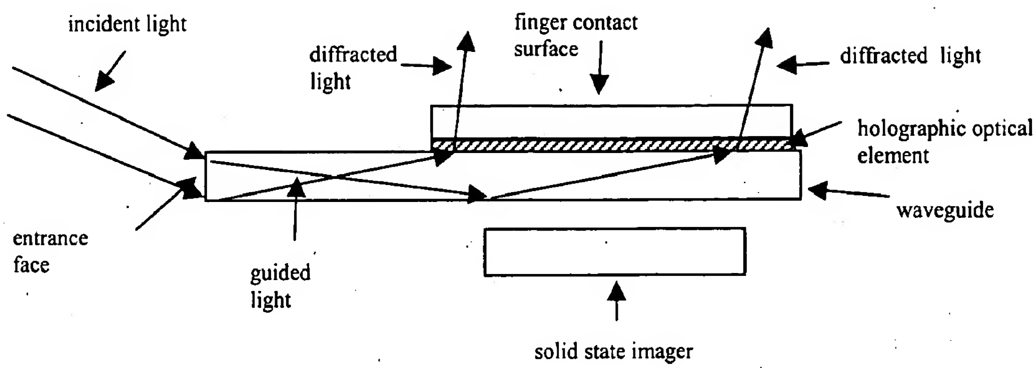


Figure 1

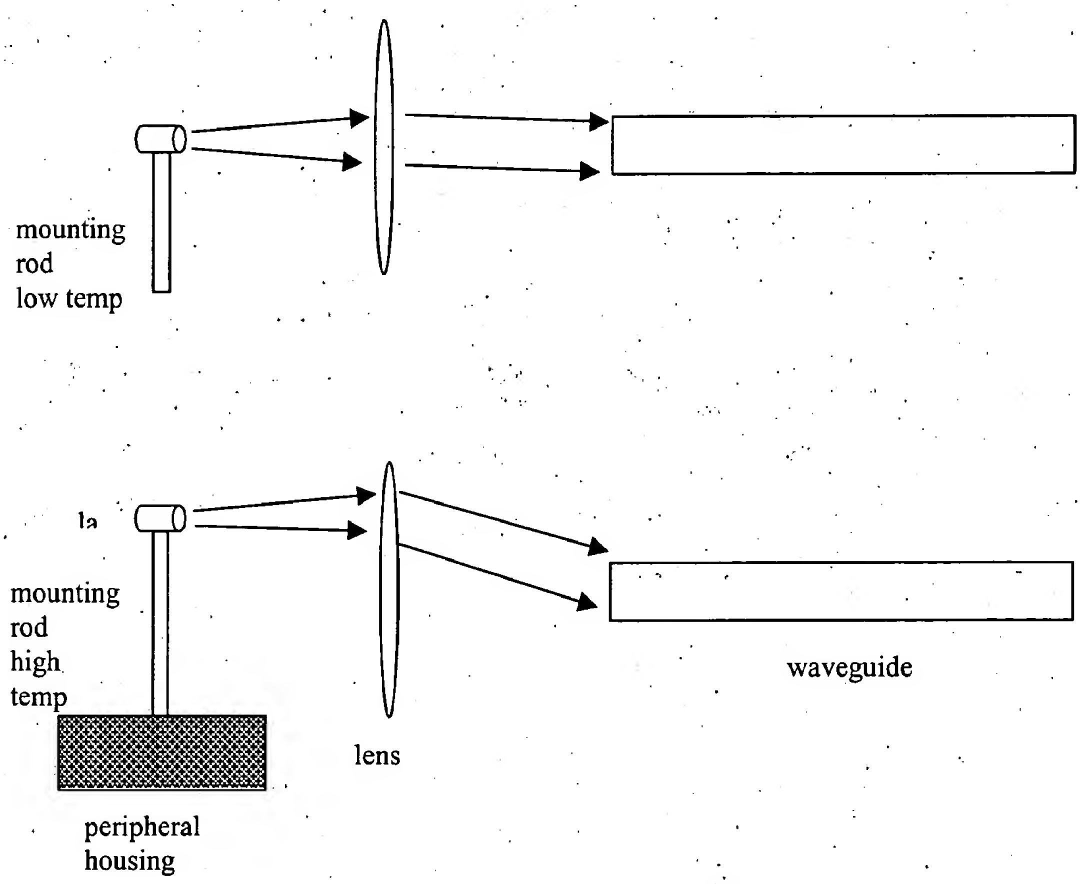


Figure 2.

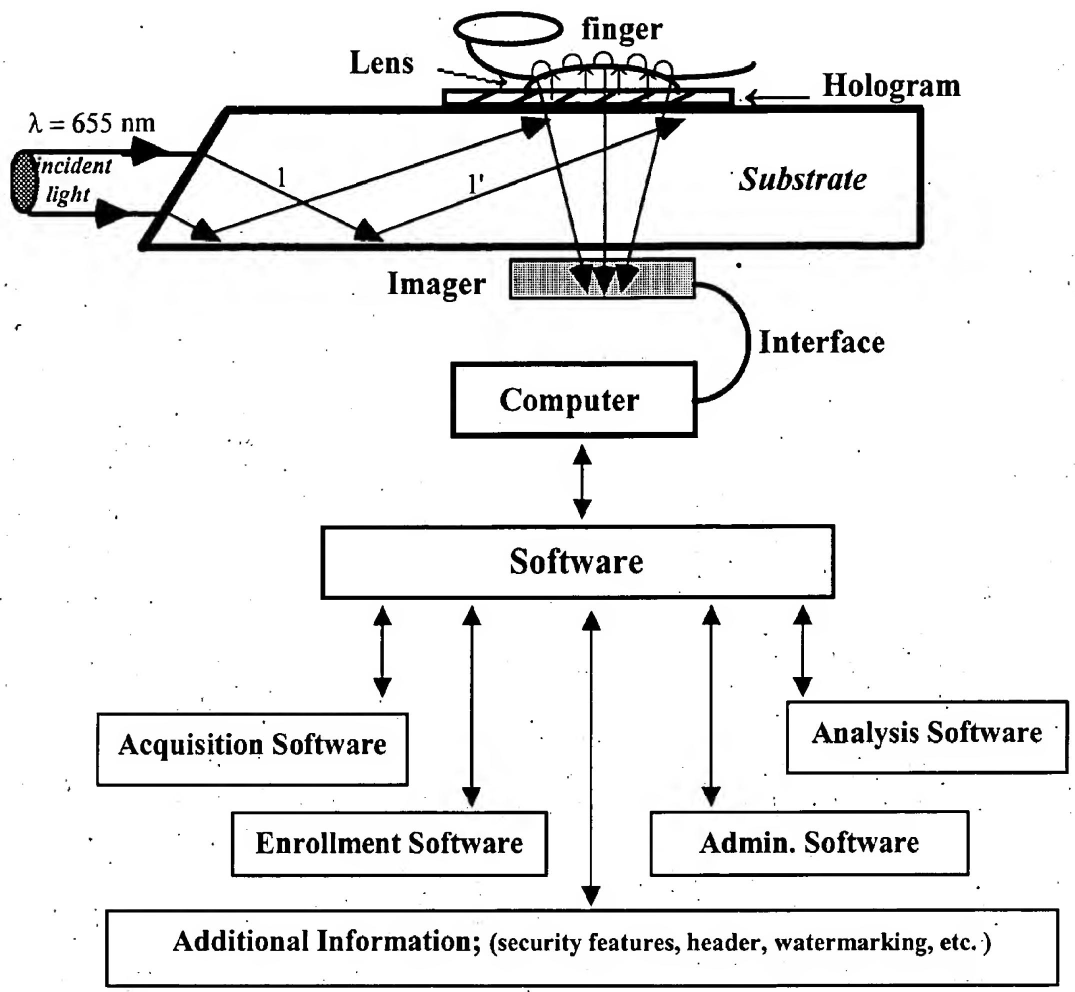

finger
Lens
Hologram
λ = 655 nm
incident
light
1
1'
Substrate
Imager
Interface
Computer
Software
Acquisition Software
Analysis Software
Enrollment Software
Admin. Software
Additional Information; (security features, header, watermarking, etc.)

Figure 3

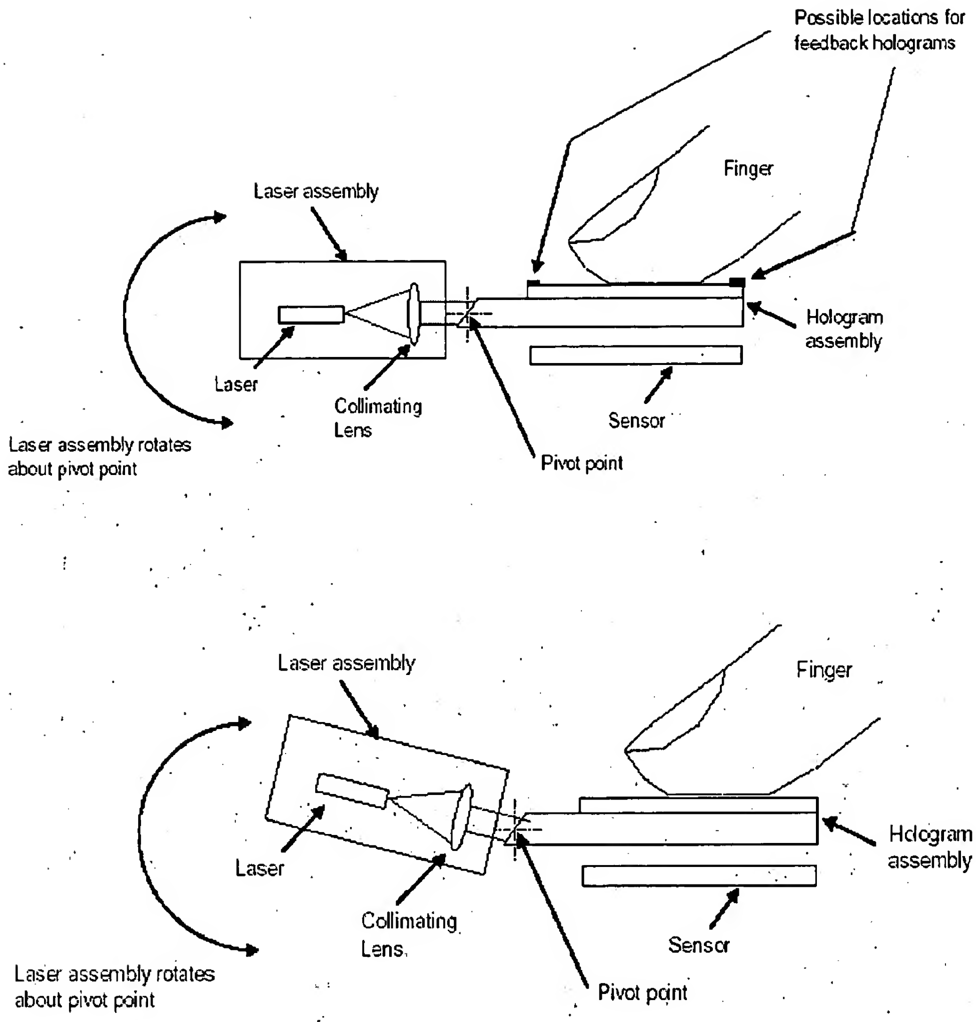
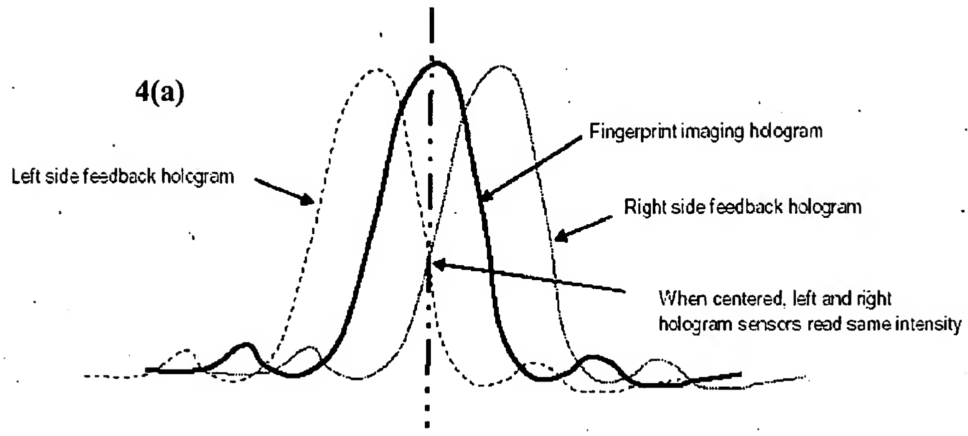


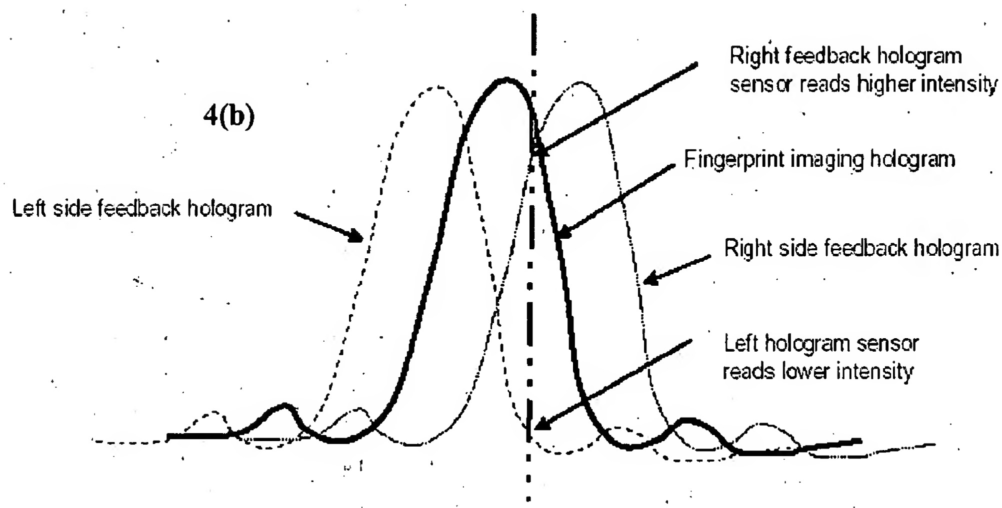
Figure 4. Schematic showing an example of an apparatus for acquiring fingerprint images wherein a closed loop servo feedback signal is provided by use of two "feedback" holograms for control and adjustment of the angle of the read laser source relative to the hologram substrate block of the hologram assembly.

4(a)



Nominal temperature

4(b)



Change in temperature has shifted the peaks to the left

Figure 5. Schematic showing in **5(a)** Bragg selecting detuning characteristics for hologram used to acquire fingerprint image (fingerprint imaging hologram; center bold line), and for holograms at higher angle (right side feedback hologram) and lower angle (left side feedback hologram) that are used to acquire information for closed loop feedback and servo control of an actuator that operates to maintain alignment of the read angle for the fingerprint imaging hologram as temperature changes in the material comprising the fingerprint imaging hologram, and in **5(b)** Shifting of the reconstruction angle for Bragg matching condition of the fingerprint imaging hologram due to a change in temperature of the material comprising the fingerprint imaging hologram.

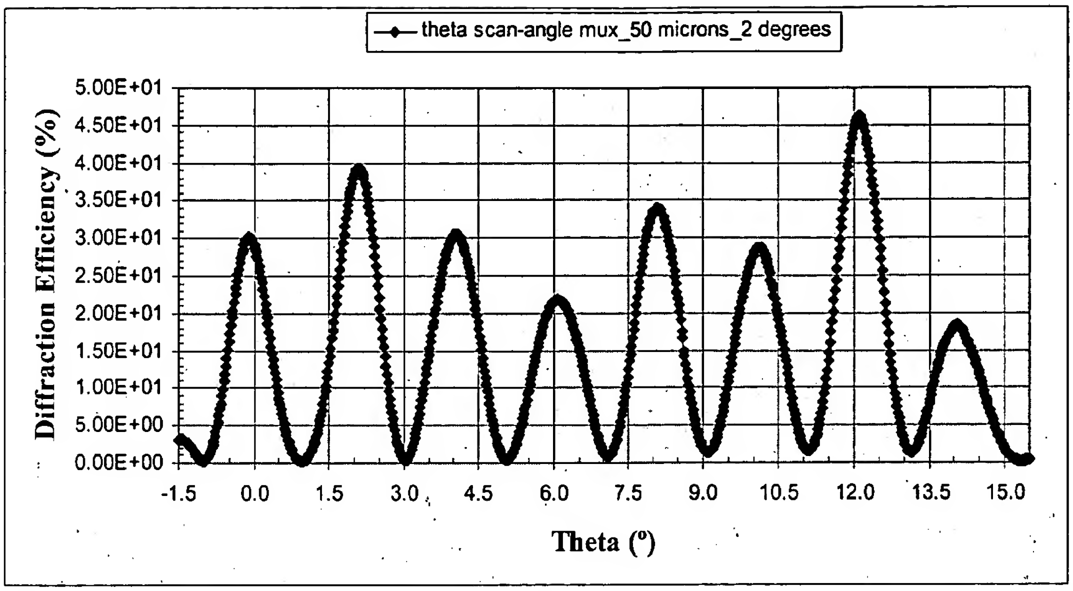


Figure 6. Co-locationally multiplexed slant fringe plane-wave holograms recorded in 50 micron thick USLH-500-7A Aprilis holographic recording medium using angle multiplexing, where the increment of the recording angles corresponds to twice the value for the full angle width at half height of the Bragg detuning curves.

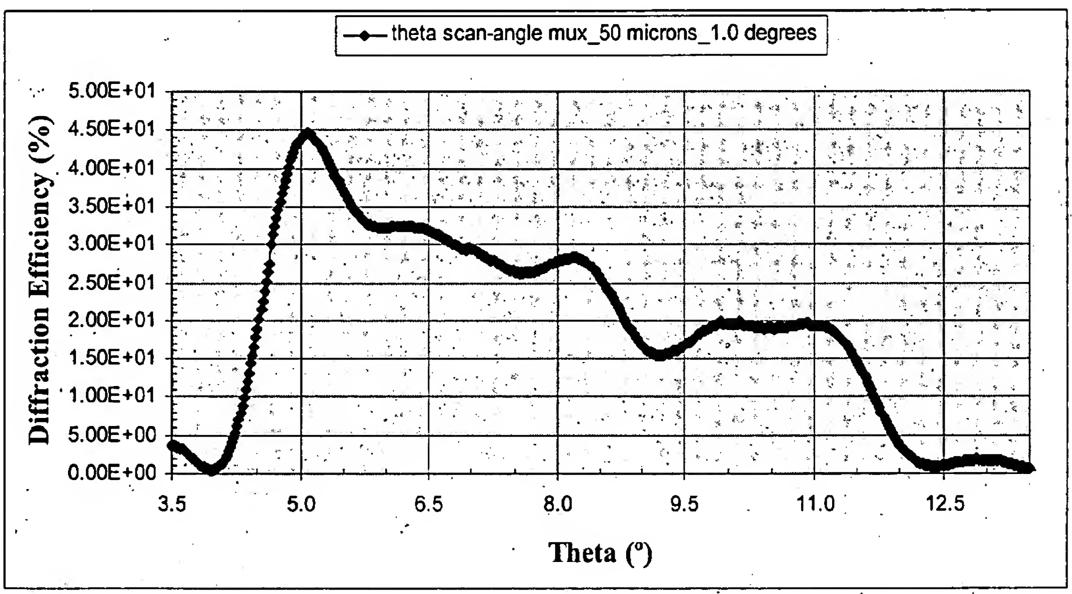


Figure 7. Co-locationally multiplexed slant fringe plane-wave holograms recorded in 50 micron thick USLH-500-7A Aprilis holographic recording medium using angle multiplexing, where the increment of the recording angles corresponds to the value for the full angle width at half height of the Bragg detuning curves.

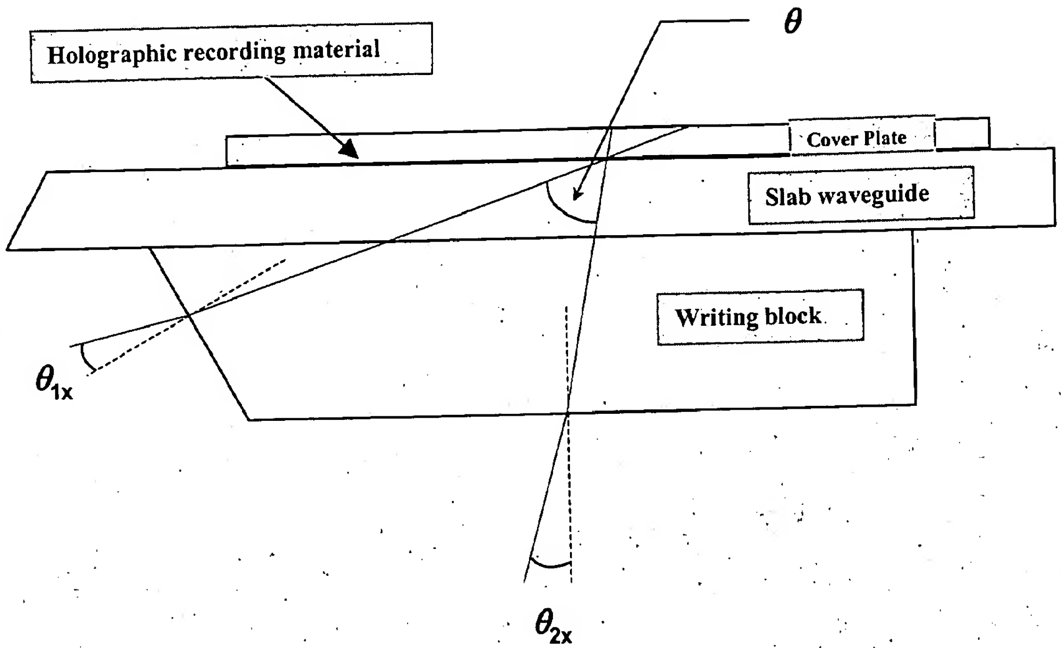


Figure 8. Schematic representation for a recording geometry of an assembly that can be used to record one or more holograms that are to be reconstructed in an edge illuminated format so as to provide for diffracting light upward from the slab waveguide for acquiring fingerprint images for an embodiment of the apparatus and method of this invention.

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Apparatus and method for high resolution fingerprint capture and identification

Field of the Invention

This invention relates to the field of fingerprint acquisition, enrollment, identification, and or authentication. It applies, in particular, to the use of a compact fingerprint imaging peripheral device that can image and capture pore structural features in addition to standard minutiae structures. The apparatus and method of this invention further comprises a data bus connecting one or more said peripheral(s) to one or more computer(s) and/or storage devices, and image acquisition and analysis software that can correlate pore structural features in addition to and/or together with standard minutiae structures. Holographic technology can be used in an optical element of the fingerprint imaging peripheral.

Background of the Invention

Growing concerns regarding domestic security have created a critical need to positively identify individuals as legitimate holders of credit cards, driver's licenses, passports and other forms of identification. The ideal identification process is reliable, fast, and relatively inexpensive. It should be based on modern high-speed electronic devices that can be networked to enable fast and effective sharing of information. It should also be compact, portable, and robust for convenient use in a variety of environments, including airport security stations, customs and border crossings, police vehicles, home and office computing and entrance control sites of secure buildings.

A well established method for identification is to compare a fingerprint with a previously obtained authentic fingerprint of the individual. Fingerprints have traditionally been collected by rolling an inked finger on a white paper. Since this traditional process clearly fails to meet the criteria listed above, numerous attempts have been made to adapt an electronically imaged fingerprint method to address new security demands. These modern proposals all use, as a key component, a solid-state device such as a capacitive or optical sensor to capture the fingerprint image in a digital format. By using a new type of solid-state imager as part of a fingerprint identification apparatus a fingerprint can be collected conveniently and rapidly, for example, during a security check, and subsequently correlated, in near real-time, to previously trained digital fingerprints in an electronic data base that resides either in a computer at the security check point, a secure but portable or removable storage device, or on a remotely networked server.

A typical fingerprint comprises a pattern of ridges separated by valleys, and a series of pores that are located along the ridges. The ridges are usually 100 to 300 μm wide and can extend in a swirl-like pattern for several mm to one or more cm. Said ridges are separated by valleys with a typical ridge-valley period of approximately 250-500 μm. Pores, roughly circular in cross section, range in diameter from about 50 μm to 250 μm and are aligned along the ridges and can be isolated or grouped into two or more abutting or near abutting features. Almost all present-day fingerprint identification procedures use only ridge/valley minutiae patterns. These are simplified and identified as a pattern of ridge/valley features such as end points, deltoids, bifurcations, crossover points, and islands, all together referred to as *minutiae.* Typically, a relatively large area of the fingerprint is required in order to obtain enough unique minutiae features, for example, at least 0.50 x 0.50 inches. Most modern fingerprint imagers therefore use up to one (1) full inch square or even larger, in order to obtain enough features to perform a useful means of identification. Fingerprints are compared using primarily this simplified description of the minutiae patterns.

Due to the extraordinary resolution requirements necessary to successfully image pores, there are no commercial devices available today that use pores for fingerprint identification, even though there are typically 7 to 10 ten times as many pores as minutiae in a given fingerprint area. We have shown that the use of pores combined with the usual minutiae significantly increases the reliability of fingerprint comparisons, and substantially reduces the false accept rate, as well as providing positive identification with use of fingerprint sample areas as small as 0.1 x 0.1 inches. A typical fingerprint image as small as 0.1 x 0.1 inches may only contain 2-5 minutiae points, not enough to reliably identify a unique individual. The same area, however, may typically contain as many as 40 to 50 pores, which along with a few minutiae points can positively identify an individual reliably.

Most optical designs proposed for creating fingerprint images suffer important limitations that reduce their usefulness in real life applications. Many designs are not suitable to resolve pore patterns for example. Other designs produce distorted images that complicate fingerprint correlation, and still other designs are too bulky or delicate for convenient use in the field. Metz, et, al., (" Device for forming and detecting fingerprint images with valley and ridge structure", Michael Metz, Carl Flatow, and Nicholas Phillips, US patent 5,974,162, 10/26/1999) have described optical designs that are capable of producing high-resolution fingerprint images. These designs combine a slab-type waveguide, a holographic grating, and a solid-state imager to produce and capture fingerprint images.

One example of such a design is shown in Figure 1. A hologram is included between a top cover plate and a bottom transparent plastic or glass waveguide slab. A light source is positioned a few cm from the entrance face of the waveguide, and a transfer optic, such as a spherical or cylindrical lens, may be positioned between the laser and the guide to couple light into the waveguide. Light propagates down the waveguide via a series of reflections at its top and bottom surfaces. The reflections occur at a propagation angle that is sufficient to produce total internal reflection. The guided light

strikes the holographic grating with an angle of incidence that is determined by its propagation angle, and a portion of the guided light is diffracted from the waveguide to a vertical or near vertical direction which propagates towards the top surface of the cover plate. With nothing in contact with the cover plate the light will be partially reflected at the plate:air interface to be redirected through the cover plate, hologram, and substrate block onto the solid-state imager located directly below the waveguide. When a finger is pressed onto the cover plate fingerprint ridges will make optical contact with the plate. Light reflection will be suppressed from these contact regions so the remaining reflected light will carry fingerprint image information, such as that originating from valleys and pores, to the imager. A significant fraction of the light that is not reflected at the cover plate surface is reflected or scattered by the finger back to the imager and produces a noticeable background noise in the captured fingerprint image. In spite of the noise, valleys, ridges, pores and minutiae are obvious in the resulting fingerprint images. In these images the valleys are bright, the ridges are gray, and the pores appear as bright circles arranged within the gray ridges.

This invention is not limited to using the optics of Figure 1. Any other method that can acquire an electronic fingerprint image with low distortion and with a resolution greater than 1100 dpi can be incorporated into a device that falls within the scope of the present invention.

Summary of the Invention

The apparatus and method of this invention is a new and advantageous implementation of fingerprint acquisition, enrollment, identification, and or authentication that comprises one or more compact fingerprint imaging peripheral(s) that can image and capture pore structural features in addition to standard minutiae structures. In one embodiment the apparatus and method of this invention further comprises a data bus connecting said one or more peripherals to one or more computers or storage devices, and image acquisition and analysis software that can correlate pore structural features in addition to standard minutiae structure. The apparatus and method of this invention operates to acquire high resolution electronic images of a fingerprint, said images having resolution of at least 1100 dpi and having minimum size of about 0.1 inch by 0.1 inch. Holographic technology can be used in an optical element of the fingerprint imaging peripheral.

The apparatus and method of this invention in one embodiment further operates to enroll high resolution electronic images of a fingerprint, said images having resolution of at least 1100 dpi and having minimum size of about 0.1 inch by 0.1 inch. In another embodiment the apparatus and method of this invention still further operates to analyze said acquired and enrolled fingerprints in a manner that provides for correlation of pore structural features in addition to standard minutiae structural features. Combination of said high resolution fingerprint device with said image acquisition and analysis software operates to provide an advanced identification capability that can identify and/or authenticate an individual from a smaller area of a fingerprint than previously achievable with commercialized devices.

The specific novel advantages of this apparatus and method are described in further detail as required, by including preferred and alternative embodiments that, by

way of example, can improve image contrast, or increase reliability of automatic fingerprint identification, or improve maintenance of precise optical alignment between the light source, the waveguide, the hologram and the electronic imager, or can operate for transmission, analysis, storage and management of fingerprint images in a manner that is appropriate and convenient for numerous specific security, forensic and other identification and/or authentication applications, or is capable of reliable operation in the field, or combinations thereof.

The fingerprint imaging peripheral of this invention comprises an optical design that in one embodiment is based upon use of a waveguide hologram, as shown in Figure 1, but design of said peripheral is not limited to use of a hologram. The design could, by way of example, instead use one or more prisms or other conventional optics to redirect light. The optics for the embodiment shown in Figure 1 is an optical design comprising; a light source; a light transmitting substrate slab or waveguide that comprises top and bottom surfaces that are substantially parallel; light entrance and light exit faces; a holographic optical element in optical contact with either the top or bottom surface of the waveguide, said holographic optical element comprising one or more holograms and being operable to diffract light that is transmitting through the waveguide such that said diffracted light exits the slab through its top surface; a means of coupling light from the light source into said light transmitting substrate through its light entrance face in a manner such that the light has a wavefront curvature and propagation angle that is substantially uniformly diffracted by said holographic optical element; a means to automatically change the light propagation angle in said substrate slab or change the wavelength of the light source, or combinations thereof, in response to changes in operating temperature of said fingerprint imaging peripheral, in a manner such that the light transmitting through said substrate slab is substantially uniformly diffracted by said holographic optical element without significant changes in diffraction efficiency over a useful operating temperature range that, by way of example, can be, but is not limited to, a range of 15°C to 40°C; at least one finger contacting surface, and at least one electronic image capture device that, by way of example, can be a CCD or CMOS imager. Said invention additionally contemplates designs that accommodate even broader ranges in operational temperature, such as between about -25°C to 55°C.

In one embodiment the electronic fingerprint images are stored directly by transfer of the fingerprint image information through a bus(s), such as a high-speed data bus(s), to a storage device(s) connected to a local or remote networked computer(s). The bus interface can be capable of outputting fingerprint image data in digital or analog form, or combinations thereof. In another embodiment the electronic bus interface can transfer remote commands to the fingerprint imaging peripheral to adjust various operating conditions of said peripheral such as laser output power, angle, temperature compensation, image exposure settings, and the like for procedures such as automatic calibration, self maintenance and automatic fault notification via the advanced interface protocol and application specific call via software controls. Said storage device(s), that are connected to a local or remote networked computer(s) can, by way of example, be an integrated storage device such as Compact Flash or Smart Media or Memory Stik, or an ATA device, or combinations thereof. Other storage devices that may be integrated and be particularly advantageous for said apparatus and method of this invention are also contemplated.

In still another embodiment of the apparatus, the electronic fingerprint images can be stored locally in the fingerprint imaging peripheral(s) and said fingerprint image information can be transferred through a bus(s), such as a high-speed data bus(s), to a storage device(s) connected to a local or remote networked computer(s). The bus interface can be capable of outputting fingerprint image data in digital or analog form, or combinations thereof. In another embodiment the electronic bus interface can transfer remote commands to the fingerprint imaging peripheral to adjust various operating conditions of said peripheral such as laser output power, angle, temperature compensation, image exposure settings, and the like for procedures such as automatic calibration, self maintenance and automatic fault notification via the advanced interface protocol and application specific call via software controls. Said storage device(s), that are part of said fingerprint imaging peripheral or are connected to a local or remote networked computer(s) can, by way of example, be an integrated storage device such as Compact Flash or Smart Media or Memory Stik, or an ATA device, or combinations thereof. Other storage devices that may be integrated and be particularly advantageous for said apparatus and method of this invention are also contemplated. In another embodiment of the apparatus the bus interface connects the fingerprint imaging peripheral(s) to one or more computers and storage devices by interface connecting protocols that, by way of example, can be IEEE 1394 (Firewire), USB, Serial ATA, ethernet and the like. Other bus interfaces and connecting protocols, that may be specifically advantageous for certain applications of fingerprint acquisition and identification, are also contemplated by the apparatus and method of this invention. By way of example, said interface-connecting bus can incorporate one or more automatic protocols for various purposes that can be useful for certain specific operations and functionalities of the apparatus.

In another embodiment of the apparatus and method of this invention said acquired image is further enhanced with additional information that, by way of example, can be one or more additional security features. Certain types of additional information can be attached to each acquired fingerprint image such as, by way of example, being attached as a header to the acquired fingerprint image. Said additional information can, by way of example, comprise watermarking, copy and counterfeit protection, or manufacturer, model and serial number of the imaging acquisition device, or date and time of the acquisition of said fingerprint, or IP address of the computer to which the imager was attached at the time of capture, or attachment of digital signature, and combinations thereof, or other useful additional information depending upon the specific device and application.

Another feature of said method and apparatus of this invention includes use of encryption methods that allows only the intended recipient to open, read, and/or use the fingerprint information, said fingerprint information can include the acquired image information or said additional information, or combinations thereof.

In another embodiment of the method and apparatus of this invention the fingerprint images are analyzed using both pore structure features and standard minutiae structures such that said analysis of pore and minutiae structures can be performed independently in a sequential or concurrent manner, or can be carried out together. By way of example, high-resolution image analysis of standard minutiae features can be

performed for backward compatibility to existing (i.e., dated) databases with the same devices used to carry out high resolution pore/minutiae analysis and correlations. A preferred embodiment of analysis of pore and minutiae structure uses a means of grey-level, gradient-edge detection. Those skilled in the art may use other suitable methods for carrying out said analysis. A schematic of a particular embodiment of the invention is shown in Figure 3.

Detailed Description of the Invention

The peripheral of this invention comprises the opto-mechanical components, one or more solid-state imagers, an electronic interface(s), and data storage means. For in-field use the peripheral must be capable of operating over a relatively wide temperature range. Although we describe a specific embodiment of the current invention that incorporates the optical design of Figure 1, the invention is not limited to devices that use this design. Certain important characteristics of the holographic optical element are very temperature sensitive. For transmission holograms, such as illustrated in Figure 1, the fraction of light diffracted by the hologram depends both on its wavelength, and its angle of incidence with respect to the hologram plane. Adequate diffraction efficiency occurs only in narrow wavelength and angular ranges that are determined by the original recording conditions and the thickness of the hologram medium. Without appropriate adjustments to the wavelength or incident angle, temperature changes of only a few degrees will significantly reduce or even eliminate holographic diffraction of a single hologram due to the effect of temperature on the refractive index of the hologram, the grating spacing and the grating angle. Equation (1), from Waldman et al., J. Imag. Sci. and Technol. 41, 5, 497-514 (1997), shows the effect of changes in refractive index, Δn, and changes in readout angle, Ω, on the magnitude of the transverse component, K_z, of the grating vector for a typical slant fringe hologram in said holographic optical element.

$$\Delta K_z = \frac{2\pi}{\lambda}\left(\frac{\sin\Omega_{2_{ext}}\cos\Omega_{2_{ext}}}{\sqrt{n^2-\sin^2\Omega_{2_{ext}}}}\Delta\Omega_{2_{ext}} - \frac{\sin\Omega_{1_{ext}}\cos\Omega_{1_{ext}}}{\sqrt{n^2-\sin^2\Omega_{1_{ext}}}}\Delta\Omega_{1_{ext}}\right) + \frac{2\pi}{\lambda}\left(\frac{\Delta n}{n}\right)\left(\frac{n^2}{\sqrt{n^2-\sin^2\Omega_{1_{ext}}}} - \frac{n^2}{\sqrt{n^2-\sin^2\Omega_{2_{ext}}}}\right) \qquad \textbf{(1)}$$

A practical device for use in the field must either eliminate operating temperature variations, or compensate for temperature changes by changing the propagation angle of the guided light, or the wavelength or both. Although means to control or reduce temperature variations, such as fans and thermal electric coolers, can be incorporated into the peripheral they add expense, require greater power consumption, and increase bulk and complexity. It has been found that reducing the thickness of the holographic medium, selecting a substrate material having similar thermal expansion properties as the holographic medium, or adjusting the slant beam angle in the holographic recording process, using holograms that have recorded with a process so as to achieve a value of grating strength, ν, of $\nu/\pi \geq 0.5$, referred to as overmodulation, alone or in combination, are effective ways to reduce operating temperature sensitivities. The apparatus of this

invention compensates for operating temperature variations by automatically changing propagation angle or wavelength to maintain adequate signal-to-noise (SNR) at the imager. A method of this invention that, by way of example, can be used to automatically adjust the propagation angle is to mount either the light source or the transfer optics, or the waveguide or any combination of the three, on one or more brackets whose dimensions change with temperature due to the thermal expansion of the mounting components. Said method is simple, inexpensive, robust, and compact, does not use any electrical power, and does not require any external control. Although one embodiment of this general approach is illustrated in Figure 2, other examples obvious to those skilled in the art are also contemplated by this invention. Figure 2 shows a laser diode light source that is positioned several cm in front of a collimating lens, which in turn is held several cm in front of the entrance face of the waveguide. The laser is mounted on a rod whose length and thermal expansion coefficient are chosen to preferably produce the vertical motion of the laser position that is required to properly adjust the light propagation angle through the waveguide as the operating temperature of the device changes. Alternate embodiments of this general concept include, but are not limited to, translating or rotating the lens, tilting the waveguide, and simultaneously moving and tilting the laser, all in response to changes in operating temperature. These motions can all be achieved automatically via temperature induced changes in the dimensions of the structural elements that form the mechanical mounts for these optical components.

The fingerprint apparatus of this invention further contemplates that an electronically controller actuator, such as a motor, can be used to adjust the angle of the read laser source relative to the hologram substrate block. The signal to drive the actuator, by way of example, can be obtained from the intensity of the light reaching the imager used to read the fingerprint, or, alternatively, from a separate imager specifically included for this purpose. In a preferred embodiment it is desirable to use light diffracted by the hologram as the feedback source, since local temperature changes such as due to contact with the finger are thereby accounted for. In one embodiment comprising use of light diffracted by the hologram, intensity of both the diffracted and undiffracted light can be monitored by separate detectors and the difference signal normalized to the sum signal can be obtained to provide feedback information for both the magnitude and direction of adjustment, relative to a set point, that is required to compensate for temperature changes. Alternatively, a second hologram, specifically for the purpose of generating a servo feedback signal, can have been recorded so as to be located in the vicinity of the main hologram that is used to acquire the fingerprint image. In a preferred alternative embodiment this second hologram that operates for providing feedback can be co-located with said main hologram by having co-locationally multiplexed the second hologram. It may be preferable to use more than a second such hologram, and the method and apparatus of this invention contemplates that one experienced in the art will choose the optimum number of such holograms to be used for generating a desired servo feedback signal for controlling and adjusting the angle of read laser. Figure 4 shows schematically an apparatus wherein two holograms are used for generating a servo feedback signal so as to provide for adjustment of the angle of the read laser source relative to the hologram substrate block. The example depicted in Figure 4 is intended to be illustrative of an embodiment of the described method and apparatus, and the use of a collimated laser for the read laser assembly is representative but is not a requirement for acquiring fingerprint

images. The hologram that is used for the feedback signal can recorded so that it operates to diffract light to a separate feedback imager, or alternatively to pixels on the imager of the fingerprint device that are located outside the area used for acquiring fingerprint images. During operation of the apparatus of this invention, the light from the read laser of the fingerprint apparatus is directed to pass at a specific angle(s) through the hologram that is used for acquiring the fingerprint, and thus the amount of light that is diffracted will be a function of the degree of matching between the properties of the hologram and the wavelength, angle, polarization, and wavefront of the read beam. Increases or decreases in temperature of one or more of the opto-mechanical components of the apparatus of this invention can operate to change the grating angle of the slant fringe hologram due to thermal expansion or contraction of the material comprising the hologram(s). Consequently, an angular mismatch results when reconstructing the hologram at an angle that was Bragg matched for a different temperature, thereby causing a loss in the intensity of the diffracted light that results in a concomitant change of intensity of the acquired fingerprint at the imager.

Different algorithms can be used to implement the servo control and proper selection of a method that is particularly suitable for a fingerprint apparatus and the computer control thereof will be obvious to one experienced in the art. By way of example, if it is sufficient to set the angle once at a known time(s), such as during an initial calibration of the apparatus, then the actuator control can be instructed to move in one direction and monitor the intensity at the electronic image capture device (i.e. solid state imager) during said movement. If the detected intensity is decreasing, then the direction of movement of the actuator can be reversed to find the optimal angle corresponding to maximum diffraction efficiency for the hologram that is used to acquire the fingerprint image. Once the detected intensity has traversed through a peak as a function of adjustment of the angle, then the actuator can be returned to its position that corresponded to the peak value of the detected intensity. Alternatively, if continuous compensation is preferred, then the actuator can be dithered back and forth traversing across the peak value of the detected intensity. In this manner the described algorithm controls the actuator so as to continually reverse direction as it crosses the peak value of detected intensity. Preferably, the actuator may be continuously moved in order to provide for sensing whether the peak has shifted in angle. It is preferable that dither amplitude be controlled such that the resulting intensity changes detected at the imager are sufficient to detect, but not so large that they deleteriously affect the SNR of the acquired fingerprint image. In another embodiment (see Figure 5), other holograms, that have been recorded so as to be Bragg matched at angles that are significantly shifted in angle in either direction relative to the angle for the diffraction peak of the hologram that is used for acquiring the fingerprint image, could be outside of the area used to acquire the fingerprint image as a means of providing for additional feedback control and sensitivity to changes in temperature. Separate imagers or, alternatively, other pixels on the imager of the fingerprint device that are located outside the area used for acquiring fingerprint images, can be used for said feedback and actuator control. In said embodiment the algorithm for servo control could drive the actuator so as to provide for keeping both of the separate imagers detecting the same level of intensity, thereby operating to maintain alignment of the hologram, that is used for acquiring the fingerprint image, so as to be centered in the read beam. For instance, if said first separate imager is

detecting higher intensity, the actuator could move counterclockwise for adjustment, whereas if second separate imager is detecting higher intensity then the actuator is driven clockwise for adjustment. In this manner, by way of example, the method of this embodiment provides both magnitude and direction to the servo control system.

Changing the light propagation angle in the waveguide will also change the angle of the diffracted light that operates to produce the fingerprint. Consequently, the position of the fingerprint image will move on the solid-state imager. Fortunately, only relatively small changes of angle are required to maintain acceptable diffraction efficiency over reasonable operating temperature ranges. Said imager can additionally be translated to accommodate larger ranges of operating temperature and such translation can also be automated as may be needed for larger temperature ranges.

An alternative embodiment comprises use of multiplexed holograms for the holographic element such that the Bragg selectivity of said holograms is substantially overlapped as a function of detuning angle. Use of multiplexed holograms that are recorded co-locationally for said element can significantly reduce the sensitivity of the apparatus of this invention to temperature changes, or alignment changes, or wavelength changes, or combinations thereof. Said holograms, by way of example, can be multiplexed by the method of planar-angle multiplexing in a manner such that the increment of the recording angle is less than the width of the Bragg selectivity of each multiplexed hologram. Alternatively, said holograms can be multiplexed by varying the interbeam angle or the wavelength such that the grating period of each multiplexed hologram is slightly different so that the angular or wavelength selectivity characteristics of one such holograms is partially overlapped with another. The optical convolution of said multiplexed holograms provides a broadened detuning characteristic for said holographic element for angle or wavelength, such that the diffraction efficiency of the element is more uniform when changes in wavelength, alignment, or temperature occur. This type of holographic element is advantageous compared to when the Bragg selectivity is broadened by the approach of over modulation.

Another alternative method, comprising changing the wavelength (see Eqn. 1 above), can also be used to compensate for temperature variations. Implementation of this alternative method maintains or stabilizes the position of the fingerprint on the imager. Wavelength changes can, by way of example, be effected by changing the operating conditions of a laser diode, such as by changing the level of the driving current for the laser, or the operating temperature of the laser, or by temperature sensitive wavelength filtering of a multi-wavelength light source such as a LED. Possible wavelength filters include, but are not limited to, holographic optical elements whose properties will change in concert with the properties of the hologram of the waveguide.

In other embodiments, rather than changing the wavelength, a reading source that has a broader wavelength spectrum can be used to reduce the sensitivity to temperature. Such reading sources may include, for example, a superluminescent LED. Still another effective approach, depending upon the properties of the hologram, is to convert the reading source to a collimated laser or LED source.

Other embodiments of the apparatus and method of this invention relate to the hologram that operates as a holographic grating to redirect the light from the slab

waveguide towards the finger. Prior art for the compact fingerprint apparatus comprises a hologram that diffracts light from the slab waveguide in a direction that is perpendicular to the top cover plate shown in Figure 1. The apparatus of this invention preferably comprises a hologram that diffracts light from the slab waveguide in a direction that is not perpendicular to the cover plate so that the light reflected at the plate:air interface will not be diffracted by said hologram on the return path toward the imager. More preferably, the hologram diffracts light in a direction that differs from the perpendicular direction by an angle that exceeds the angular width of the Bragg selectivity of said hologram, but said angle is additionally as close to perpendicular as possible in order to minimize distortions in the imaged fingerprint. The preferred diffraction property of said hologram can also be achieved with multiplexed holograms or with overmodulated holograms providing for both the preferred angle of the diffracted light and also the preferred broadened angular selectivity of said hologram.

Another aspect of the apparatus and method of this invention, is that it comprises one or more holograms that operate as a holographic grating to redirect the light from the slab waveguide towards the finger in a direction that differs from the perpendicular direction by an angle that exceeds the angular width of the Bragg selectivity of the one or more holograms, and that said hologram(s) is also formed to operate with a diffraction efficiency of at least 10%, more preferably at least 50%, even more preferably at least 75%, and most preferably greater than 90%. In prior art (Metz et al.) the hologram of a compact fingerprint apparatus was a single hologram that would be formed to optimally operate with a diffraction efficiency of specifically 50% to maximize the amount of detected signal that reflected at the plate:air interface.

Other embodiments of the apparatus of this invention relate to the slab waveguide that operates to propagate light from said light source via TIR conditions to the location of said hologram. In one embodiment the apparatus and method of this invention preferably comprises a slab waveguide that includes an entrance edge that has an oblique angle to the top and bottom surfaces, said surfaces being substantially parallel and planar surfaces. Use of an oblique angle for the entrance face of the slab waveguide advantageously reduces the thickness requirement for said slab waveguide. In another embodiment the apparatus and method of this invention preferably comprises a slab waveguide that has an entrance edge, which operates with optical power to optimize illumination of the location of the hologram without use of external optical elements. By way of example, said optical power can be designed to provide optimal illumination of said holographic grating for laser diodes that operate to output light with a certain divergence angle range that changes the height and/or width of the output light. In still another embodiment said apparatus and method comprises a slab waveguide that includes light traps at its end. In still another embodiment said slab waveguide can, by way of example, have a reflective metal coating along its bottom surface at or near the entrance edge of the waveguide. Said coating operates to protect the slab waveguide from smudges and other defects that can impair the signal-to-noise (SNR) of the apparatus. In other embodiments, a ½ wave plate is included between a laser source and the entrance edge of the slab waveguide to rotate the plane of polarization such that the polarization is matched to the polarization used to record the holographic optical element while at the same time providing optimal illumination of the entrance edge of the slab waveguide.

The ½ wave plate can be tilted on an axis perpendicular to the direction of illumination in order to provide an effective optical thickness that is optimal for a given wavelength.

Other embodiments of the apparatus and method of this invention relate to the top cover plate that operates to sandwich the hologram with the slab waveguide. In one embodiment the apparatus and method of this invention preferably comprises a top cover plate that has high refractive index relative to BK7 or float glass. Said cover plate can then redirect undiffracted light more efficiently by means of reflecting the light, which, by way of example, can be under TIR conditions. In another embodiment said top cover plate comprises a curved finger contact surface that, by way of example, is a plano-convex lens. Said curved surface can, for example, be used to capture larger images and enhance signal strength. In still another embodiment said curved surface is another optical element that is attached to a planar top cover plate, or is placed on top of the planar top cover plate when the fingerprint is captured. In still another embodiment the apparatus and method of this invention comprises a compliant polymer coating that is located on the finger contact surface and operates as the surface material that the finger contacts. Said coating can, by way of example, can be attached to the cover plate, or it can be part of the cover plate, or it can be placed onto the cover plate when the fingerprint is captured. Said coating can be used to enhance image quality and reduce the dependence of SNR in the acquired fingerprint image on finger moisture or the wetting characteristic of the finger surface to the cover plate. In still another embodiment the apparatus and method of this invention comprises a cover plate that is formed from a material that has a refractive index that optimizes SNR of the captured image, such as fused silica.

Other embodiments of the apparatus and method of this invention relate to other components and methods that can increase SNR of the captured fingerprint image. Additional optical components that, by way of example, can include use of a ¼ wave plate in combination with a linear polarizer to reduce detection of noise that can arise undesirably from sources such as diffuse and specular reflection. In this manner the contrast of the fingerprint image can be improved. In one configuration, said ¼ wave plate can be sandwiched between the optical element below it, that covers the hologram, and another optical element above it, that is the top cover plate, and the linear polarizer is located beneath the slab waveguide and above the imager. Said hologram operates to diffract light that is linearly polarized in a direction upward towards the ¼ wave plate, and upon propagating through the ¼ wave plate the polarization is transformed to circularly polarized light. Upon reflection from either the top cover optical element or from ridge structure of the finger, the circularly polarized light is transformed by the ¼ wave plate back into linearly polarized light that has an electric field direction that is orthogonal to the original direction of the light entering the hologram. Both diffuse and specular reflection occurs due to interaction of light, diffracted by the hologram, with the ridge structure of the finger surface that is in contact with the cover element, whereas only specular reflected light occurs where the diffracted light interacts with said top cover plate, and various embodiments thereof, at locations that correspond to the valley or pore structure features of the finger surface. Detection of the noise contributions from said reflected light can substantially increase the level of grey-scale detected for portions of the captured fingerprint that would otherwise most desirably be zero grey scale level or black. High grey-scale levels for areas of the fingerprint image that otherwise should be

black can substantially reduce contrast in the captured image and thus make image analysis more difficult. The diffuse reflected light can be partially to fully depolarized, and thus the polarizer can be oriented to at least partially block contributions of said diffuse reflected light from being captured by the imager, thereby improving contrast. Other methods of improving contrast are also contemplated by this invention. Said linear polarizer can be used in combination with said wave plate, as described above, or can be used alone as an optical element to improve SNR, said optical element being positioned in the optical path between the top cover plate and the imager which by way of example can be one or more CCD or CMOS imagers.

It has been found that selecting a source wavelength that is in a range of wavelengths that are effectively absorbed by the finger (e.g., blue light) reduces diffuse reflected light, thereby improving contrast.

It has been further found that additional improvements in SNR can be achieved by use of antireflection coatings on any of the surfaces that may reflect light other than the top cover plate that operates to sandwich the hologram with the slab waveguide. Similarly, use of transparent dielectric layers, that, by way of example, can be flexible polymeric film materials such as silicones or siloxanes characterized by having a low glass transition temperature, to eliminate air gaps between surfaces that may reflect light, can improve SNR further by operating to substantially reduce the intensity of the light that originates from such reflection(s).

CCD and CMOS imagers are currently preferred for fingerprint capture. A peripheral can contain one or more of these devices. According to the work of Roddy and Stoz (Fingerprint Features-Statistical Analysis and System Performance Estimates, Feb. 10, 1999) the imager should have a resolution of at least 1100 bpi so that pores in fingerprints can be resolved. Since the optical design of Figure 1 does not use a lens the fingerprint is captured without magnification. The maximum size of the finger that can be imaged in this manner is equal to the active area of the imager. We have demonstrated accurate fingerprint identification using analysis and correlation of minutiae and pore structures that were acquired from an area of the finger that is less than about 1/8" by 1/8". The current standard method that uses analysis of minutiae solely calls for a finger area that is typically about 1" by 1".

An electronic interface that is capable of outputting image data of the fingerprint image in digital or analog form is connected to the imager. Said digital image data can be stored locally in the peripheral using an integrated storage device such as Compact Flash, Smart Media, Memory Stik, or ATA device, or combinations thereof. Other storage devices that may be integrated and be particularly advantageous for said apparatus and method of this invention are also contemplated. In a more typical embodiment the electronic fingerprint images may be stored directly by transfer of the fingerprint image information through one or more buses, such as a high-speed data bus(s), to one or more storage devices that are connected to one or more local or remote networked computers. Said data can also be output directly to one or more bus-compatible remote storage devices. Said storage device(s), that are connected to one or more local or remote networked computers can, by way of example, be an integrated storage device such as Compact Flash or Smart Media or Memory Stik, or an ATA device, or combinations thereof. Additionally, for the case when said digital image data is stored locally in the

peripheral using an integrated storage device, then said data can be subsequently stored to one or more storage devices that are connected to one or more local or remote networked computers.

The fingerprint apparatus can make use of such storage devices for storing freshly obtained images, or previously captured images, or previously enrolled and trained images (known heretofore as templates or models), or combinations thereof. Further, when a storage device nears its capacity the system comprising said apparatus of this invention, in another embodiment, can automatically prompt the system administrator to backup or provide additional local or remote storage allocations, or automatically re-allocates storage as determined by a previously scheduled configuration setting, or combinations thereof. By way of example, the electronic interface can also transfer remote commands to said peripheral of the apparatus of this invention, that allow controlled adjustment of various conditions in said peripheral such as laser output power, angle, temperature compensation, and image exposure settings, and the like, thus allowing for automatic calibration, or self maintenance and automatic fault notification via the advanced interface protocol, or application specific calls via software controls, or combinations thereof.

A high speed, serial or other data bus connects the peripheral of this invention to one or more computers that can store, enroll, analyze, and otherwise manage the electronic images. Examples of interface connecting protocols include, but are not limited to, IEEE 1394 (Firewire), USB, and Serial ATA. The connecting interface bus can incorporate an automatic protocol for identifying and registering the type of imaging device to the operating system when plugged in to the computer, and then for launching various computer applications and scripts that automatically prompt the user to acquire, store, enroll, train, and otherwise manage, use and administer the fingerprint system. Said peripheral can be powered via the bus-interface, eliminating, in many cases, the need for separate power supplies, including use with remote and/or portable devices such as laptop computers. The interface protocol can also provide a means to automatically identify additional serialized devices, such as when they are added to the system, and to allow similar functionality or expanded functionality, such as multiple fingerprint imaging stations.

Additionally, in another embodiment, after images are captured by said peripheral, and indexed and stored, then certain software-based enhancements may be performed, if needed, at the option of the system configuration administrator or for other beneficial reasons. Certain enhancements that do not alter the original image or its unique characteristics can be performed to enhance image analysis, such as mean low-pass filtering, or automatic level adjustment to improve contrast, or other methods that include, but are not limited to, grey-scale gradient edge detection techniques for pattern recognition and subsequent matching techniques, or combinations thereof.

Software capable of comparing previously trained images or smaller portions of images can be compiled as templates of an individual fingerprint that comprises both minutiae and pore structure features. Standard ridge, valley, and minutiae patterns may be combined with pores, pore clusters and specific details can be ignored or tagged as required features in order to qualify a correlation as successful. These techniques as applied to fingerprint/pore detection will provide unique, novel, and very robust methods

of positively identifying and/or authenticating an individual, compared to those previously used with traditional 500 dpi resolution imagers and standard minutiae based methods. Applications for forensics as well as other identification and authentication will be practical, with the use of this invention, on a large scale and at low cost. This invention will have significant commercial and forensic impact, as pore structures are unique to the individual, and are present in many times the quantity than standard minutiae data (see Roddy and Stosz, Fingerprint Features-Statistical Analysis and System Performance Estimates, Feb. 10, 1999).

Self calibration combined with real-time adaptive training can be implemented with the apparatus and method of this invention to keep the fingerprint database of trained models current, and, additionally, can be automated with software designed to self-train templates, that by way of example, are based upon grey scale gradient-edge detection techniques as applied to fingerprint/pore image analysis. Other forms of image analysis that can be automated and applied to fingerprint/pore image analysis are also contemplated. By way of example, each time an individual uses an imager of this invention, a new template can be stored that can be trained automatically or with manual intervention, if desired, said new stored template being added to the current fingerprint database for that user, thus increasing the reliability of the apparatus of this invention by improving its ability to eliminate both false rejects and also false accepts by use of unique feature training. With multiple trained templates for an individual, the false reject rate can be improved dramatically by automatically adding high resolution models to the fingerprint database for said users on the occasion of subsequent read events. Accordingly, the more said user accesses the apparatus of this invention, the better said apparatus is able to adapt to normal changes and fluctuations in minor surface aberrations that otherwise can cause other lower resolution minutiae-based or blob-based systems to fail. In addition, since the pore concentration often provides up to about 10 times the amount of data that is available from minutiae features alone, positive identification can frequently be achieved with a much smaller sample than previously possible. Said advantages will provide significantly higher success rates in the forensic field, and also with use for a child's fingerprint, which often can not be reliably resolved with less than 1100 dpi resolution imaging devices.

In another embodiment of the apparatus and method of this invention said acquired fingerprint image is further enhanced with additional information that, by way of example, can be one or more additional security features. Certain types of additional information can be attached to each acquired fingerprint image such as, by way of example, being attached as a header to the acquired fingerprint image. Said additional information can, by way of example, comprise watermarking, copy and counterfeit protection, or manufacturer, model and serial number of the imaging acquisition device, or date and time of the acquisition of said fingerprint, or IP address of the computer to which the imager was attached at the time of capture, or attachment of digital signature, and combinations thereof, or other useful additional information depending upon the specific device and application.

Another feature of said method and apparatus of this invention includes use of encryption methods that allows only the intended recipient to open, read, and/or use the fingerprint information that has been acquired, enrolled, analyzed or enhanced, or

combinations thereof, said fingerprint information can include the acquired image information or said additional information, or combinations thereof.

In applications of the apparatus and method of the invention, an acquired fingerprint image is correlated against one or more stored fingerprint images. In many cases, the fingerprint images are likely to have been acquired using different imagers. To minimize the effect of distortion in the acquired images, an NIST traceable alignment target can be used to calibrate each imager device. The alignment target can be, for example, a plate having a grid or array of dots on its surface. A calibration file can be created for each imager device and stored for reference. In this manner, an image acquired on imager device A with certain distortion can be corrected or scaled relative to an image of the same fingerprint acquired on imager device B with certain other distortion characteristics.

The apparatus and method of this invention, which provides aforementioned advantageous aspects of fingerprint imagers in combination with integration software, will provide for a peripheral device that is capable of extremely high resolution and accurate correlation, such as is necessary for a device that is to be used with electronic banking, online transactions, and security, authentication and identification applications.

Exemplification

We describe here a fingerprint correlation experiment as a reduction to practice that highlights the value of the apparatus and method of this invention. A fingerprint of the forefinger of the right hand of one our staff was recorded in 1996 using the optical design shown in Figure 1. Total image area captured of said fingerprint was approximately 0.15 x 0.15 inches. The fingerprint as captured was displayed on an analog video monitor and a black and white photograph of the image was obtained using a Polaroid instant camera with high contrast black and white film. Subsequently, said photograph of said fingerprint was stored under ambient conditions. In 2003, 6.5 years later, said Polaroid photographic image was digitized by scanning at 600 dpi, and used as a training template for an example of the fingerprint correlation software of this invention. A new image of the same finger was acquired in 2003 using a fingerprint imager of this invention comprising the optical design of Figure 3, excepting that the top cover glass used for said reduction to practice was flat and parallel to the surface of the slab waveguide. Said captured fingerprint was compared to the 6.5-year-old photograph of the original. A positive identification, using both pores and minutiae, was readily achieved, even though the said original and new images represent a finger area only 1/8" by 1/8", scale and rotation were different, and contrast and exposure were not matched nor calibrated in any way. At least 50 features, including 45 pores and 5 minutia points were captured from the original scan of the 1996 image, of which 22 pores and 5 minutia were present, detected and matched in said captured fingerprint imaged in 2003. Said successful correlation results show that including pores in the fingerprint by use of an apparatus that is capable of acquiring fingerprint images at high resolution, greatly increases the number of features that can be used for image correlation and significantly enhances the reliability of fingerprint comparison. Beneficial effects of the enhancements provided by the apparatus and method of this invention provide for reducing the occurrence of false acceptance, improving (through use of multiple templates) false reject rates, and significantly reducing the fingerprint sample area required for positive unique

authentication.

Figure 6 shows the Bragg detuning characteristics for 8 co-locationally multiplexed slant fringe plane-wave holograms recorded in 50 micron thick USLH-500-7A Aprilis holographic recording medium. Recording was carried out in the conventional using angle multiplexing where the increment of the recording angles for each of the co-locationally multiplexed holograms corresponds to twice the value for the full angle width at half height of the respective Bragg detuning curves. Each hologram was recorded with equal beam intensities of 4 mW in the Reference and Signal beam paths using spatially filtered and collimated light with a fixed value for the interbeam angle of 48.6°, and the sample was rotated about the vertical axis by increments of 2° for each subsequent recording. Recording times used for the sequential recording of the co-locationally multiplexed hologram were varied in order to achieve similar diffraction efficiency for each of the holograms, as the recording sensitivity of the multiplexed holograms were about 27, 30, 24, 16.75, 15.65, 7.9, 4.2 and 1.2 cm/mJ, respectively, for holograms #1-#8. The cumulative grating strength for the 8 multiplexed holograms corresponds to the case where $\nu/\pi \geq 1$, and thus a substantially overmodulated hologram could have been recorded as a single plane-wave hologram. When the separation angle between the multiplexed holograms is reduced to an increment equal to the full width at half height of the Bragg detuning curve, then the resultant Bragg selectivity curves of the holograms are convoluted as shown in Figure 7. The range of diffraction efficiency shown in Figure 7 as a function of the value of Bragg detuning angle was not optimized for achieving a more desirable top hat type manifold. Nevertheless, the results in Figures 6 and 7 are illustrative of the use of multiplexed holograms to provide for a means of compensating for temperature variations of the fingerprint device.

Figure 8 shows a schematic representation for a recording geometry and assembly that can be used to record one or more holograms that are to be reconstructed in an edge illuminated format for acquiring fingerprint images for an embodiment of the apparatus and method of this invention. The external angles of the reference and signal writing beams, with respect to the perpendiculars to the surfaces they are each incident on, are θ_{1x} and θ_{2x}, respectively, and the internal interbeam angle between the writing beams is defined as θ. The bottom most truncated trapezoidal flat is referred to herein as the writing block and is used in this embodiment to couple light into the recording assembly so as to provide for a large internal incident angle for the signal beam. The holographic recording material is located below the top cover plate and above the truncated trapezoidal flat directly below, and is depicted schematically as a bold solid line. In a preferred embodiment the holographic recoding material is the middle of a sandwich construction comprising the top cover plate above and said trapezoidal flat below. The holographic recording material can have a wide range of thickness and those experienced in the art will be able to choose a thickness that provides for desired properties of the hologram in such an apparatus. By way of example, these properties can include diffraction efficiency and angle width for the Bragg detuning characteristics of the hologram. The truncated trapezoidal flat directly below the hologram is referred to herein as the reading substrate or slab waveguide. In this embodiment it operates to couple light incident from the edge of said slab waveguide (see Figure 1 and 3), such as from a laser source, into the reading assembly so as to provide for reconstruction of the hologram and

thereby direct light incident from reflection within the slab waveguide in the direction of diffraction by the hologram upwards toward the top cover plate of the assembly. Selection of suitable angles for the signal and reference beams, so they are optimized relative to the angle of the oblique face that is used for the entrance edge of the slab waveguide, the thickness and refractive index of the writing block and slab waveguide, and also for the desired location of the hologram along the length direction of the assembly will be obvious to those familiar with the art. Suitable angles for recording have been found to be 17.24° and 16.28° for θ_{1x} and θ_{2x}, respectively, for a writing wavelength of 532 nm and a reading wavelength of 650 nm, where the writing block is BK7.